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Developing Seismic Performance Factors for Prefabricated Bamboo Walls in Comparison to Conventional Timber Shear Walls

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SENIOR DESIGN PROJECT
REPORT

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Abstract

In order to address the issue of rising demand in resources from providing a growing population with housing, a team of professors and undergraduate students worked to study bamboo's possible utility as a structural element. This team proposed the use of bamboo as a substitute for timber in conventional light frame construction, specifically in the form of bamboo shear walls, which resist lateral loads such as those applied by earthquakes and winds. In order to demonstrate the adequacy of these proposed bamboo walls as a substitute to the control softwood walls, the team used the document FEMA P-795 to develop methods of designing, testing, and finally analyzing these walls to demonstrate structural equivalency. The results from this process would then be used to support the inclusion of the proposed walls in the 2013 Team Santa Clara Solar Decathlon House, which is in turn a step towards eventual acceptance by international regulatory and governing agencies.

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1.0.0 Introduction

The demand for housing and new buildings has been growing at an exponential rate since the end of World War II, especially in ascendant nations such as Brazil and India. Rising populations, increasingly higher standards of living, and the growth of the middle class in these nations will lead to an even larger increase in demand for construction as the 21st century continues to alter the socioeconomic landscape of the world. The material requirements necessary to meet this growing demand for new building will drive the costs of building materials up and put increased pressure on the environment. In order to address these problems, our design team desired to determine a bamboo shear wall's structural equivalency when compared to a conventional timber shear wall.

Using the document FEMA P-795 as a methodology for determining equivalency, our team designed, built, tested, and analyzed both the proposed bamboo walls as well as the a number of conventional control walls. A number of distinct bamboo components, shipped to us by a bamboo workshop in Vietnam, were integrated into a bamboo shear wall system designed to adhere as closely as possible to the conventional walls as outlined in FEMA P-795. These walls were then tested in accordance with the procedures outlined in P-795, and the resulting data reduced to provide design values that fulfilled P-795's criteria for equivalency.

With these design values, we worked to set the stage for future acceptance and usage of bamboo shear walls within the US by proposing the inclusion of these walls in the 2013 Santa Clara Solar Decathlon house.

2.0.0 Project Selection

When initially deciding on our senior design project topic, we considered several alternatives and weighed them according to several criteria. Based on both team members' previous experience working as research assistants examining bamboo's potential as a disaster relief building material in Haiti, it was clear that a senior design project involving bamboo would be a natural progression. The upcoming 2013 Santa Clara Solar Decathlon Team's desire to include a primarily bamboo structural system provided us an opportunity to continue work with bamboo, but in a significantly different context and utility: that of conventional US construction. Working to make changes to the construction industry in the US would allow us to learn not only about bamboo construction practices, but would allow us to gain familiarity with a number of design documents as well as with standard construction practices in the US. In addition, the idea of making a positive impact on the construction industry drove us further to consider bamboo as our project topic.

In specifically choosing to focus on bamboo shear walls, we considered the importance of lateral systems in a structure, as well as the increased complexity involved in developing and testing these systems. Shear walls' essential role in resisting earthquakes and winds make them highly attractive as a project topic, especially as we are located in the seismically active San Francisco Bay Area. In addition, the increased challenge associated with the testing and analysis process appealed to our desire to seek out a sufficiently rigorous project. It was these numerous factors that ultimately led to our selection of bamboo shear walls as the subject of our senior design project.

3.0.0 Project Goals and Objectives

Our goals for this project were threefold: to demonstrate bamboo's structural equivalence to timber, to provide an innovative lateral force resisting solution for the 2013 Santa Clara Solar Decathlon team, and to pave the way for future bamboo code development in the US.

Our first objective was to determine bamboo shear walls' structural equivalency to conventional timber shear walls by deriving a design value that fell within FEMA P-795's acceptable range. This would allow us to put forth bamboo shear walls as an adequate substitute for timber walls. We would then submit our findings to a Solar Decathlon building official for acceptance in the 2013 Radiant House. This would hopefully demonstrate bamboo's potential as a building material and set the stage for further development in the US.

4.0.0 Code Requirements for Conventional OSB Shear Walls

To determine the design criteria for a new structural element, especially when the considered material, bamboo, has almost no history of being accepted before in any other case, there is a long and arduous process that has been known to take years for any new structural element to become approved by any part of the many different regulatory U.S. building codes, the International Residential Code, or the International Building Code following code. To ease this, conventional structural elements similar to the proposed bamboo shear wall will serve as a guide in detailing requirements, testing requirements, and data analysis requirements. Oriented Strand Board (OSB) stapled shear walls are one of the many variations that have defined design strengths and seismic performance factors. By using these pre-defined codes as a baseline for developing the construction, testing, and data analysis for bamboo shear walls many of the uncertainties that would normally become problematic and a point of controversy in further code development cease to be an issue.

Codes can be looked at in three different categories the first being detailing. This deals with the correct structural design of the structural component. Has the correct material been used? Have the correct safety factors been applied? Are the specific seismic parameters met? Once the design is complete, detailing then becomes a construction issue. Are the local permit drawings being followed? Have fasteners been applied correctly? Are all edge conditions met with all points of anchorage properly anchored at the correct depth? These set of questions are all regulated by three different governing bodies, each deal with different parts of the construction or design process. *The Timber LRFD/ASD Wind & Seismic Design Guideline* serves as the initial code to consult when approaching design.

This will then reference *ASCE 7-10: Minimum Design Loads of Buildings and Other Structures* which will infspecified structural component, in this case light frame timber structures.

Table 1: ASCE 7-10 Table 8: Response Modification Factors, R, and Overstrength Factors, Ω, for different structures (Excerpt)

Basic Structural System and Seismic Force Resisting System	Response Modifcation Factor, R	Deflection Amplification Factor, C_D
	Bearing Wall System	
Light Frame Walls with Shear Panels	6 ½	4
Reinforced Concrete Shear Walls	4 ½	4
Reinforced Masonry Shear Walls	3 ½	3
Concentrically-Braced Frames	4	3 ½
Unreinforced Masonry Shear Walls	1 ¼	1 ¼
Plain Concrete Shear Walls	1 ½	1 ½

After determining the correct process of designing and building conventional materials, by using known applicable codes for testing the new proposed element through the same process the conventional structural element was tested to arrive at its design values, any controversy can be avoided regarding testing procedures that would bring this process to a set of design values. *ASTM, The American Society of Testing Materials* serves as the governing body for all material testing. For seismic structural elements, it outlines protocol that will be discussed during *Methods for Establishing Design Values on page X of this document.*

Finally, with the correct detailing and testing procedures observed during the construction and structural testing process, this process will propose to implement *FEMA P-795: Quantification of Component Equivalency Methodology* to analyze acquired data for a control component, the OSB shear wall, with hopes of comparing the results to the tested values for the proposed component, the bamboo shear wall. This document will be analyzed and discussed in greater depth on *page X under Methods for Establishing Design Values*. The process for FEMA P-795 follows a logical process that builds on the strict testing and analysis requirements of its predecessor *FEMA P-695: Quantification of Building Seismic Performance Factors* which requires a much more complex analysis with a higher number of tests being run for greater confidence in the results. By using *FEMA P-795*, not only is the rigorous testing and analysis requirements eliminated, but by successfully showing component equivalency response in a seismic situation, the proposed bamboo shear wall can once again follow a code defined building material eliminating criticisms in the future. By approaching seismic testing and analysis requirements through the following flow chart, *FEMA P-795* can be appropriately used.

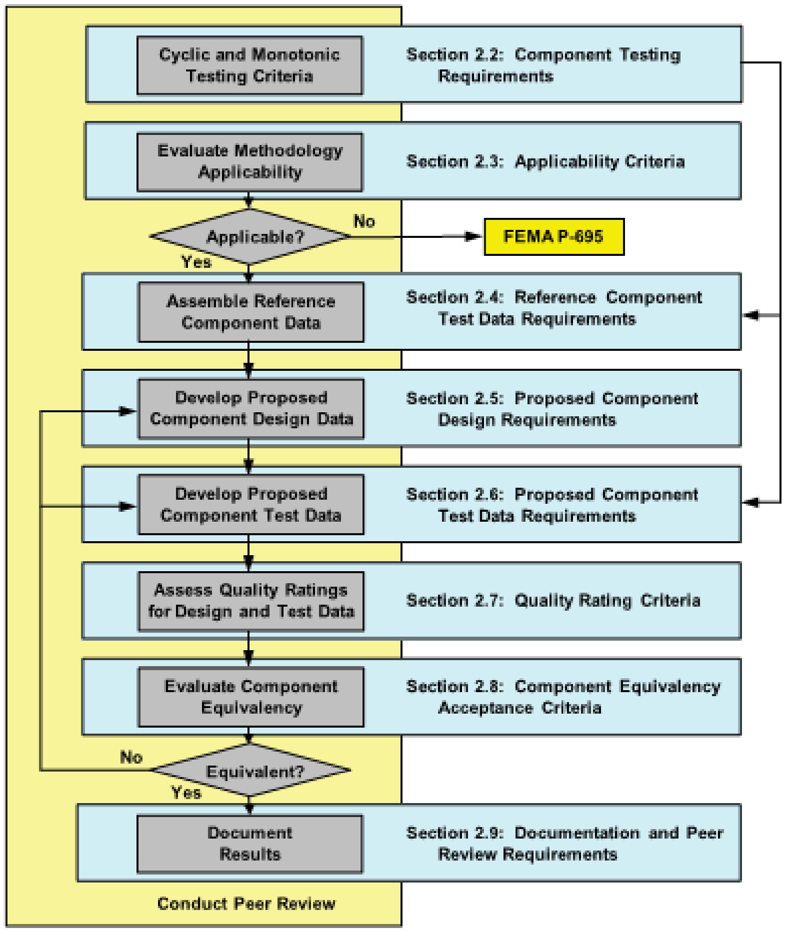

Figure 1: Process for establishing and documenting component equivalency

By appropriately using the codes below, the proposed bamboo shear wall system will be successfully constructed, tested, and analyzed to determine the appropriate seismic and strength design factors.

Table 2: Summary of Applicable Codes and Data Analysis Documentation

Building Code or Publication Document	**Scope of Document**	**Purpose of Use**
FEMA P-795 (2011)	Quantification of Building Seismic Performance Factors through Component Equivalency Methodology	To show seismic performance equivalency between bamboo shear walls and stapled OSB shear walls
ASCE 7-10 (2010)	Minimum Design Loads for Buildings and Other Structures	A reference to determine seismic performance factors for control OSB shear wall seismic performance system
ASD/LRFD SDPWS Special Design Provisions for Wind and Seismic (2008)	Timber Design Guideline for Lateral Systems	Provides specifications and detailing requirements for building timber shear walls
ASTM E 2126-09 (2012)	Cyclic Testing Method Protocol Based on Testing Requirements	Determines method of loading shear walls to determine performance
Talbot Et. Al. (2008)	Structural Performance of Stapled Wood Shear Walls Under Dynamic Cyclic Loads	The results in this document serve as a basis to FEMA P-795's test results and observations for showing seismic performance equivalency

5.0.0 Methods for Establishing Design Values

The process of acquiring design values for the proposed bamboo shear wall will take a modified approach to FEMA P-795 while strictly observing ASTM testing requirements. Because this particular system has never been used or tested before, FEMA P-795 will serve to create a range of design strength and design stiffness values that if met through a statistical analysis based on number of tests run and average distance from the mean will imply seismic structural equivalency to the control structural component, and therefore the same seismic factors of the control OSB timber shear can be directly used as the seismic factors for the proposed bamboo shear wall.

To test the shear walls, the mode of testing and the number of tests were established from the requirements chiefly governed by the base requirements put forth by *FEMA P-795: Quantification of Building Seismic Performance Factors: Component Equivalency Methodology.* Section 2, which outlines the process for component equivalency methodology, sets the requirements for the number of tests needed based on a number of factors: confidence in the control and proposed structural element, the average distance from the mean of the stiffness and the strength of each wall which must be analyzed as the tests progress, and finally the number in the case of this project was reduced because of the need for shear walls in limited areas of the 2013 Solar Decathlon House, a 1 story structure without a high risk for failure because of the high percentage of code accepted shear walls that will be used compared to the number of possible proposed bamboo shear walls that may be used.

Table 3: Quality Rating of Test Data

Completeness and Robustness of Tests	Confidence in Test Results		
	High	**Medium**	**Low**
High. Material, component, and commection behavior well understood and accounted for. All, or nearly all, important testing issues addressed.	Superior	Good	Fair
Medium. Material, component, and connection behavior generaly understood and accounted for. Most important testing issues addressed.	Good	Fair	Not Permitted
Low. Material, component, and connection behavior fairly understood and accounted for. Several important testing issues not addressed.	Fair	Not Permitted	Not Permitted

Table 4: Penalty Factor for Uncertainties (P_U)

Quality Rating of Proposed Component Test Data	Quality Rating of Proposed Component Design Requirements Relative to Reference Component Design Requirements		
	Higher	**Same**	**Lower**
Superior	0.95	1.00	1.15
Good	1.00	1.05	1.25
Fair	1.15	1.25	1.40

Table 5: Penalty Factor to Account for Difference in Component Strengths (P_Q)

Ratio of Maximum Cyclic Load for Proposed Component to Control Component ($R_{Q, PC}$ / $R_{Q, RC}$)	**Penalty Factor to be Applied (P_Q)**
0.50	1.88
0.60	1.55
0.70	1.31
0.80	1.14
0.90	1.00
1.00	1.00
1.10	1.00
1.20	1.00
1.30	1.04
1.40	1.09
1.50	1.13
1.80	1.24
2.00	1.32

By analyzing section 2 of *FEMA P-795*, it was determined that four control OSB shear walls would be tested and four proposed bamboo shear walls would be tested. This would satisfy the requirements that at least two walls of each type of variation for each type of test run. Therefore two control OSB shear walls will be tested in a monotonic loading scenario while two will be tested in a cyclic loading scenario. The same process will be repeated for the proposed bamboo shear walls.

Monotonic loading is the process of loading the tested structural element to failure in one direction, for the purpose of shear walls, this simulates the application of a wind load or direct force applied to the face of a structure that the shear wall would then need to carry to the foundation. The typical load-deformation response is shown below in figure 1. Cyclic loading is defined by the CUREE Protocol outlined in *ASTM* 2126-09 *Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of The Lateral Force Resisting Systems for Buildings.* This loading was developed to analyze how a structural component behaves when it fatigues by constantly being loaded and unloaded. For the tested shear walls, the typical loading, shown as deflection V. time in figure 2 demonstrates that the wall is loaded and unloaded repeatedly in both directions (cyclic loading) at higher and higher peak deformations past the point of failure.

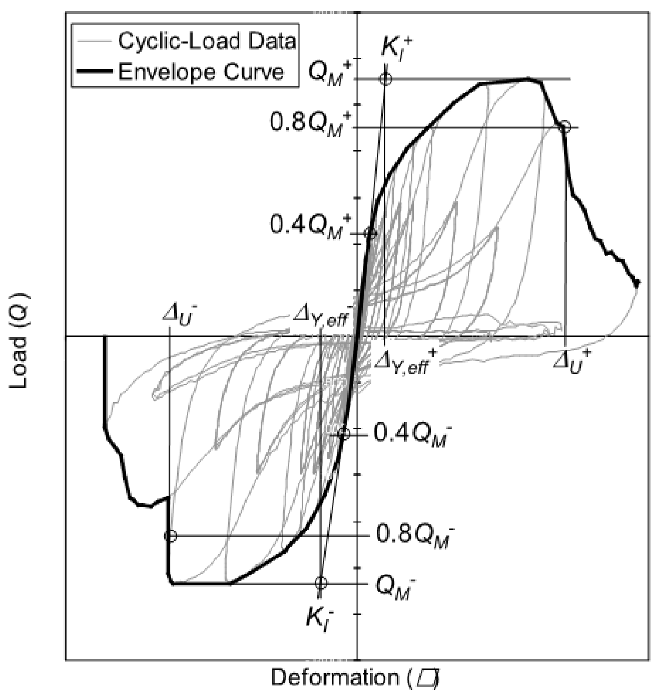

Figure 2: Illustration of a monotonic curve and determination of maximum load Q_M, and ultimate deformation, Δ_{UM}, parameters for a component test specimen.

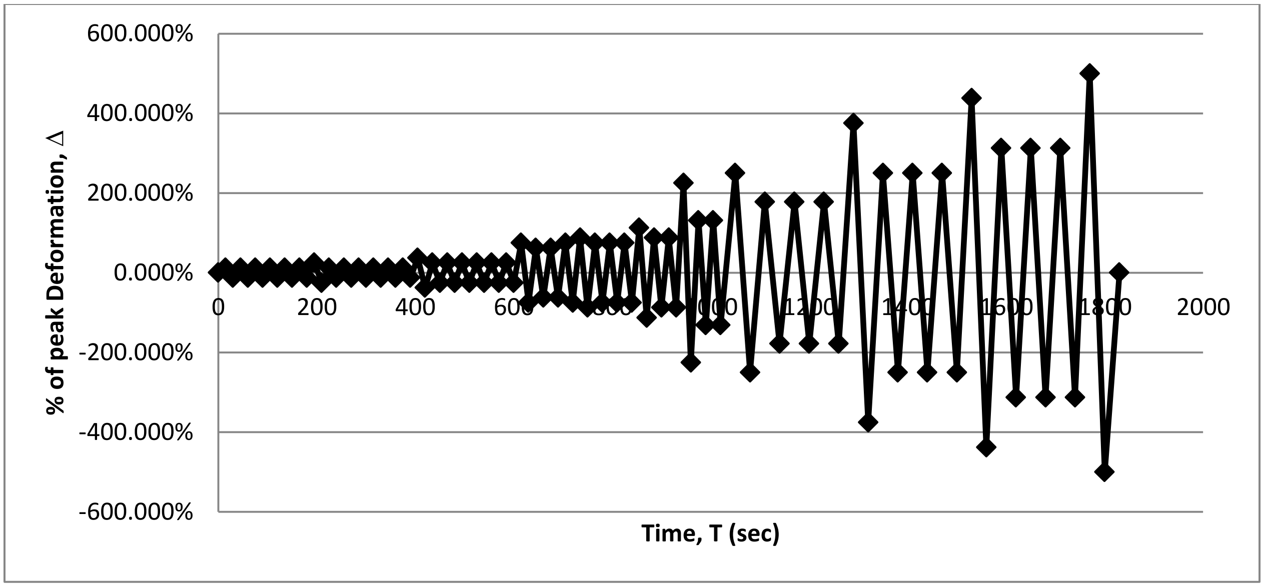

Figure 3: Loading Pattern for Cyclic Loading as Defined by the CUREE Loading Protocol

Data for both of these tests are recorded until after the peak load has been achieved and the structural element loses strength while continuing to deform until 80% of its peak load is reached, peak load is also known as Q_M.

After testing has been completed, the component equivalency methodology outlines important parameters that will have to be determined from the structural tests. These are outlined in Table 6 seen below.

Table 6: Important Parameters Established By Monotonic and Cyclic Testing

Specific Notation	**Description**
K_L	Effective value of initial stiffness of the component test specimen through the secant at $0.4Q_M$, based on positive and negative cycles of loading
Q_M	Maximum load applied to a component during cyclic-load testing, based on positive and negative cycles of loading
Q_{MM}	Maximum load applied to a component during monotonic testing
Δ_U	Ultimate deformation of a component test specimen at $0.8Q_M$ based on positive and negative cycles of loading during cyclic-load testing
Δ_{UM}	Ultimate deformation of a component test specimen at $0.8Q_{MM}$ based on monotonic-load testing
$\Delta_{Y,eff}$	Effective yield deformation of a component test specimen during cyclic-load testing based on positive and negative cycles of loading, defined by the ratio Q_M / K_L
μ_{eff}	Effective ductility capacity of a component test specimen, defined as the ultimate deformation, Δ_U, divided by the effective yield deformation, $\Delta_{Y,eff}$

By establishing these important parameters through the process outlined in Section 2 of *FEMA P-795*, and Appendix D of *FEMA P-795*, which serves as an example application. A series of equations must then be applied using these parameters that determine if structural equivalency in a seismic situation can be established. If any of the equations are not met, then the proposed component must then be tested and analyzed in accordance with *FEMA P-695* to develop its own set of seismic performance parameters. If all equations are satisfied, then the process has successfully demonstrated that all seismic performance parameters outlined by ASCE 7-10 for the control component, in this case the light frame timber shear wall, can be directly substituted as the seismic performance parameter for the new proposed bamboo shear wall. The following test results will be analyzed according to the process as described above to determine structural equivalency for seismic performance factors.

6.0.0 Construction

6.1.0 Construction Materials

6.1.1 Fasteners

In order to maintain as much consistency between the proposed and control walls as possible, the both types of walls were constructed using the same fasteners and hardware when possible. In both walls, RSP 4 Stud Plate Ties were included despite their exclusion from conventional construction processes to account for the absence of a gravity load from the presence of a structure supported by the wall.

In building the timber control walls, all fasteners and hardware used were commercially available and traditionally used in the construction of conventional shear walls.

Table 7: Fasteners used in Control Wall Construction

Timber Control Wall	Quantity
Simpson Strong-Tie RSP4 Stud Plate Tie	4
Simpson Strong-Tie 14-Gauge HDU2 Hold Down w/ 5/8” DIA. Threaded Rod	2
1 ¾ " Long x 5/8” Crown 16 Gauge Electro-galvanized Staples	1 L.S.
1” DIA. Shear Bolts	2

Fasteners and hardware used in the construction of the bamboo shear walls were kept mostly consistent with those used in the timber control walls, but with the inclusion of stainless steel self-tapping screws. These were chosen to substitute the electro-galvanized staples at the connection between the shear-panel and the top and sill plates, as detailed later in the Construction Process section. This was due to a constructability concern in the unexpected significantly higher hardness in the bamboo shear boards preventing staples from being able to penetrate through into the stud.

Table 8: Fasteners used in Proposed Wall Construction

Bamboo Proposed Wall	Quantity
Simpson Strong-Tie RSP4 Stud Plate Tie	4
Simpson Strong-Tie 14-Gauge HDU2 Hold Down	2
1 ¾ " Electrogalvanized 16 Gauge Staples	1 L.S.
1 ¾ " Stainless Steel Self Tapping Screws	1 L.S.
1" Stainless Steel Self Tapping Screws	1 L.S.
Anchor Bolts	2

6.1.2 Timber

The timber walls were constructed from commercially available materials used in conventional shear wall construction. The top and sill plates, as well as the studs consisted of #2 Douglas Fir Larch 2 by 4's. The shear panel consisted of a 4' by 8' by 15/32" thick Structural 1 OSB Board.

6.1.3 Bamboo

Bamboo components were custom-manufactured by a bamboo manufacturer in Vietnam according to specifications that our project team defined as most effective in terms of performance and constructability. These components were divided into three distinct components, each of which served as a direct analogue to one component in the control walls.

The first was a whole bamboo culm with a diameter of approximately 4”, which was dried and cut to varying lengths (See Figure 1). These culms were analogous to the 2X4 studs used in the construction of the control walls.

Figure 4: Bamboo Stud, attached to sheathing

The second component was a laminated board, measuring approximately 4’ by 8’ by ½ “ thick, composed of layers of woven bamboo which were glued together and cut to the dimensions of the OSB sheathing used in the conventional walls (See Figure 2).

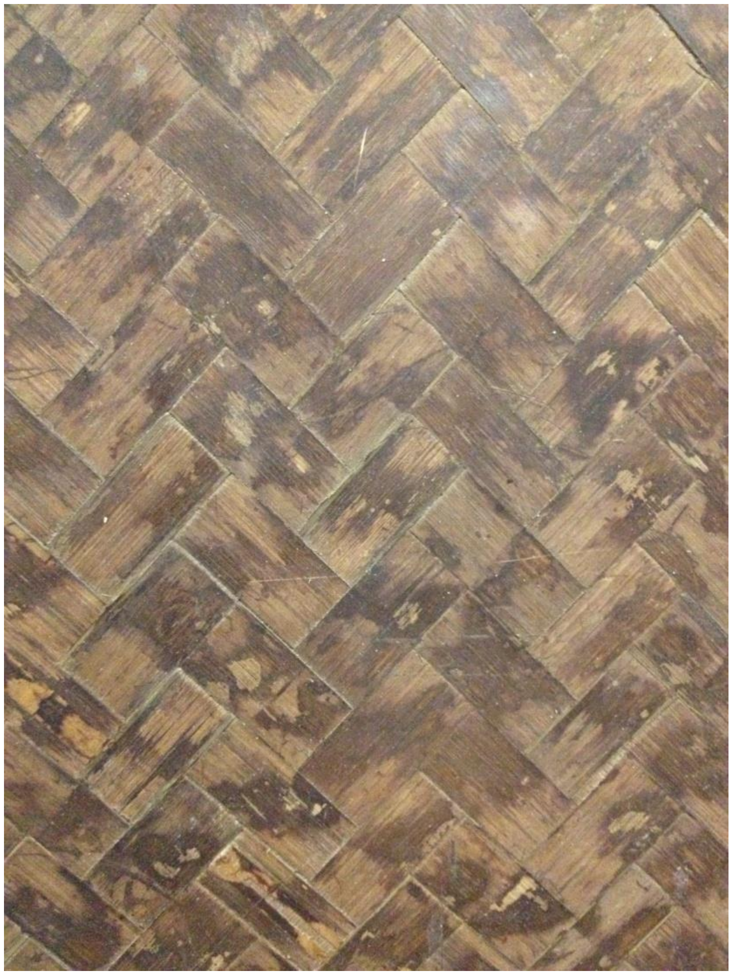

Figure 5: Detail of woven surface of bamboo sheathing

The last component, which served as a substitute for the top and sill plates, was manufactured in the same manner as the sheathing but to different dimensions. The laminated layers of woven bamboo were instead cut to dimensions equivalent to those of a softwood 2X4.

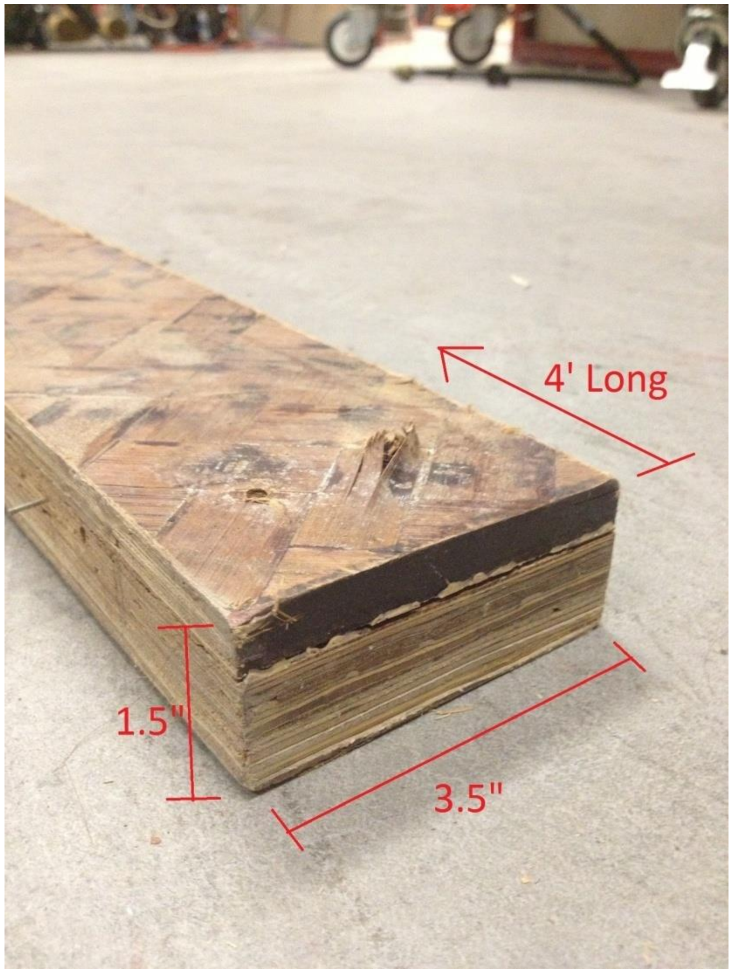

Figure 6:Top and sill plates, with superimposed dimensions

6.2.0 Construction Process

Using the construction processes outlined in FEMA P-795 Appendix D (which adhere to SDPWS detailing requirements) as a guide, we constructed a number of control timber walls and proposed bamboo walls. We attempted to replicate construction techniques used for the control walls as closely as possible when assembling the bamboo walls to maintain consistency between the two wall types.

The shear walls were constructed by attaching steel hardware and the shear board to a frame. An assembly process for this is detailed below:

1. Ensure that all timber/bamboo are the following dimensions:
    a. Sill/top plates: 4' Long
    b. Studs: 7' – 7 1/2" Long
    c. Shear board: 4' by 8'
2. Place all studs parallel to each other spaced at approximately 16" O.C.
3. Lay the top plates flush across one end of the culms and the remaining plank, or sill plate, flush across the other end. The centerline of the Westernmost (given that the top plate direction is North) culm should be aligned with the edge of the plates.
4. Connect each stud to top and bottom plates by screwing one 1 ¾" screw through the top and sill plates into the studs. This will allow the frame to maintain its geometry and dimensions.
5. Lay the shear board over the frame, ensuring edges of sheathing line up with edges of top and sill plates.

6. Staple through shear board into the two outside studs at 2” O.C. Staples should be oriented so that their long axis is parallel to that of the studs.
7. Staple through sheathing into the two interior studs at 4” O.C. Staples should be oriented so that their long axis is parallel to that of the stud.
8. A. For control walls: Staple through sheathing into sill plate at 2” O.C. Staple through sheathing into each top plate at 4” O.C. Rows of staples in each top plate should be staggered by approximately 2”.

   B. For proposed walls: Screw through sheathing into sill plate at 2” O.C. Screw through sheathing into each top plate at 4” O.C. Rows of screws in each top plate should be staggered by approximately 2”.
9. Flip wall over so that sheathing is resting on ground, and attach one RSP4 Stud Plate Tie at top and bottom of every interior stud.
10. Attach one HDU2 Hold Down at bottom of each outside stud, drilling a hole for the threaded rod through sill plate and screwing the hold down into the outside studs.
11. Drill one hole at the approximate center of the sill plate for anchor bolt insertion.

Following construction, these walls could be transported to project sites and tilted up and installed in their final positions.

Figure 7: A completed control shear wall (left) and proposed shear wall (right)

7.0.0 Experimental Testing

7.1.0 Experimental Setups

As outlined previously in **Methods for Determining Design Values**, we adhered to Section 2 of FEMA P-795 when performing our testing to determine design values. Based on a number of factors outlined in Section 2, we determined two monotonic and two cyclic tests would be performed on each type of wall.

Tests were performed at Santa Clara University's full frame testing machine (See Figure), which allowed us simulate the effects of earthquakes of wind loads on our 4' by 8' shear walls. This frame allowed for precise control of lateral deflections by moving a horizontal cross beam with a hydraulic ram capable of applying a maximum of 160 kips of force.

Figure 8: Full frame testing machine

At the top of the wall, load was applied by two steel angles fixed on either side of the wall by 1” diameter threaded rods. This allowed lateral loads to be applied while preventing extraneous axial loads from affecting our results. Additional 1” diameter threaded walls fixed in between the steel angles prevented out of plane rotation at the top of the wall due to any incidental eccentricities in loading. See Figure ? .

Figure 9: Shear wall top connection detail

The bases of the walls were connected using two different systems. For the control walls, the hold-down rods and anchor bolts were spaced such that they could be directly affixed into holes drilled into the base beam. See Figure ?

Figure 10: Control wall base connection detail

We found that variations in the diameter of the studs in the bamboo wall necessitated another system of connection at the base of the wall, so we developed a system of steel HSS sections that allowed us adjust for the slightly different hold-down spacings.

Figure 11: Proposed wall base connection detail

7.2.0 Instrumentation and Control

The testing machine's hydraulic rams were controlled by a computer program that allowed precise adjustment of deflections to the horizontal beams as well as the vertical columns. The corresponding amount of load needed to achieve these deflections was read by load cells which allowed for load-displacement curves to be generated.

The data to control the deflections of the beam were inputted either manually or as a pre-programmed data sheet which ran a time vs. displacement function. The cyclic tests were run according to one of these functions, with the CUREE loading protocol serving as the input data. The monotonic test input data was inputted manually, with a certain rate of deflection held constant.

Data was outputted in a spreadsheet format, which was used to generate our load-displacement curves and ultimately determine design values.

8.0.0 Experimental Results

The process of collecting the experimental results was broken down into the monotonic and cyclic loading cycles for both the control OSB shear wall and the proposed Bamboo Shear Wall. Because of the shear mass of data points collected during each of these tests (point taken every one tenth of a second, with tests running from five minutes for monotonic loading to forty-five minutes for cyclic loading cycles). As shown below, in figures three and four, the monotonic response of the control shear walls hits similar peak loads and hits peak stiffness at roughly the same point demonstrating the consistency of the code defined control OSB shear wall as expected.

Figure 12: Control Test A-Monotonic Loading Response of OSB Shear Wall

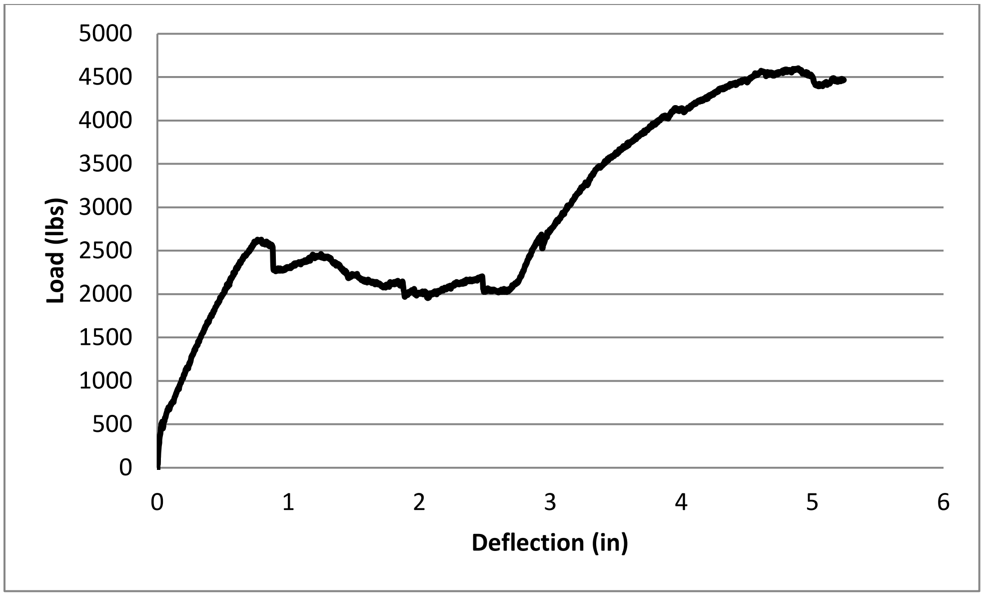

Figure 13: Control Test B-Monotonic Loading Response of OSB Shear Wall

Running the same loading tests for bamboo shear walls demonstrated expected results like a lower stiffness and lower peak loading while exhibiting a much higher ultimate deformation. This was expected solely because bamboo as a material is known for its ability to deform immensely before failure.

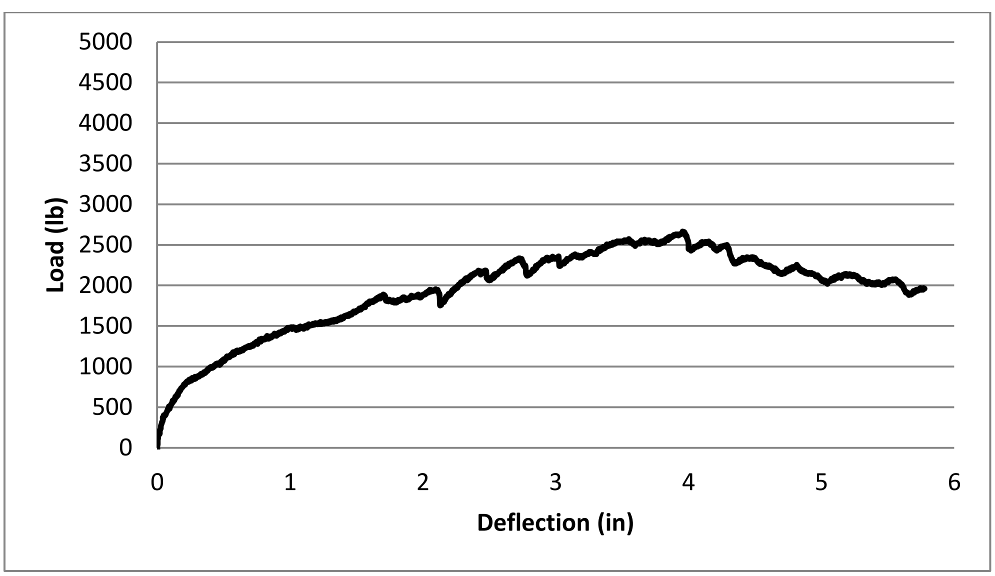

Figure 14: Proposed Test A-Monotonic Loading Response of Bamboo Shear Wall

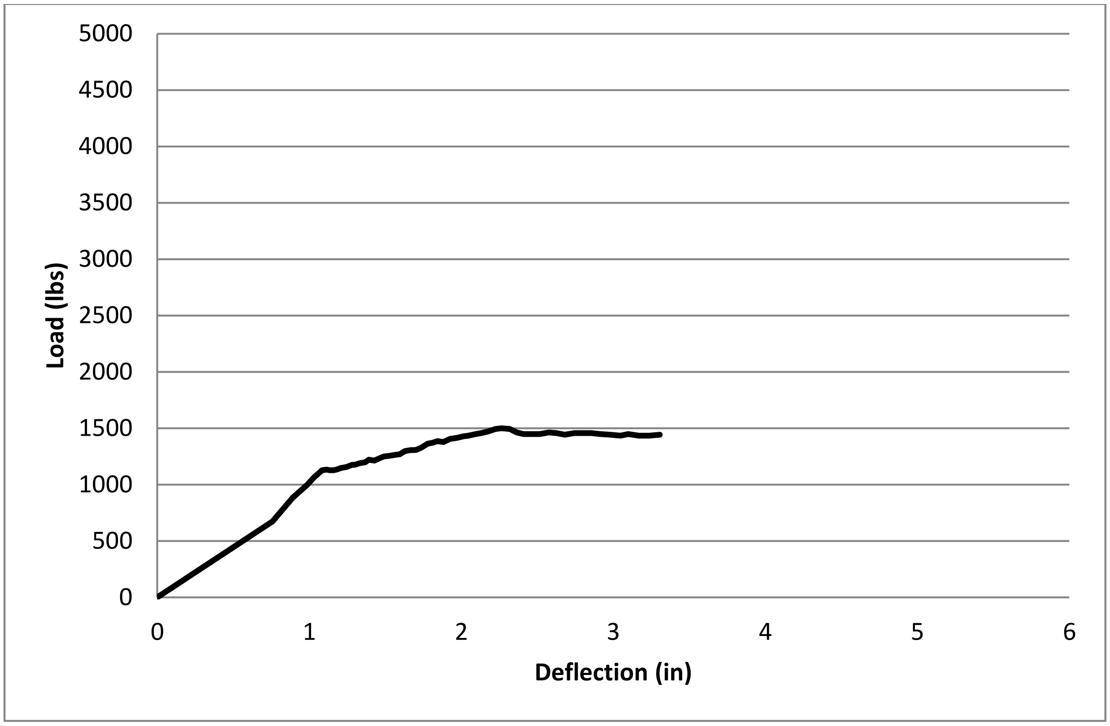

Figure 15: Proposed Test B-Monotonic Loading Response of Bamboo Shear Wall

After seeing similarities with some of the expected differences in the monotonic loading scenarios for the control component and the proposed component, the cyclic loading scenarios were performed for both wall types as well. Expecting to see similar results to those reported by *FEMA P-795* Appendix D in their analysis of OSB stapled shear walls, was not confirmed. It was determined that the testing conditions presented in *FEMA P-795* did not conform to the ones performed with the associated results below as well as the constructability of the walls tested did not meet the detailing requirements of *The ASD/LRFD Timber Wind & Seismic Design Guideline*. Therefore slightly different results were recorded and were subsequently used without any influence of the *FEMA P-795* OSB shear wall test results.

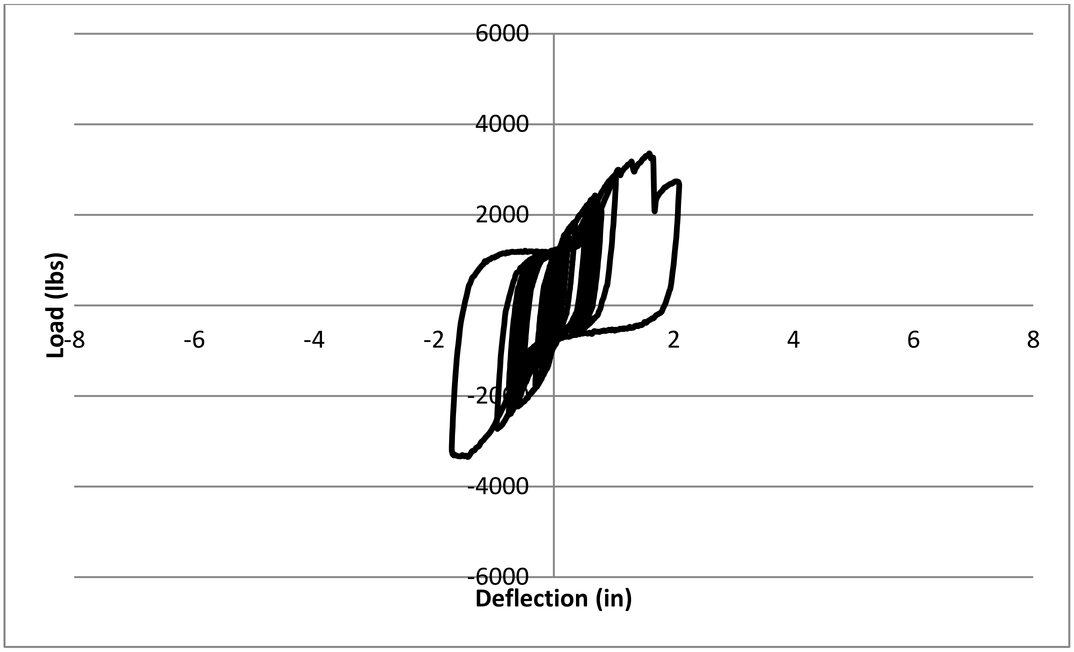

Figure 16: Control Test C-Cyclic Loading Response of OSB Shear Wall

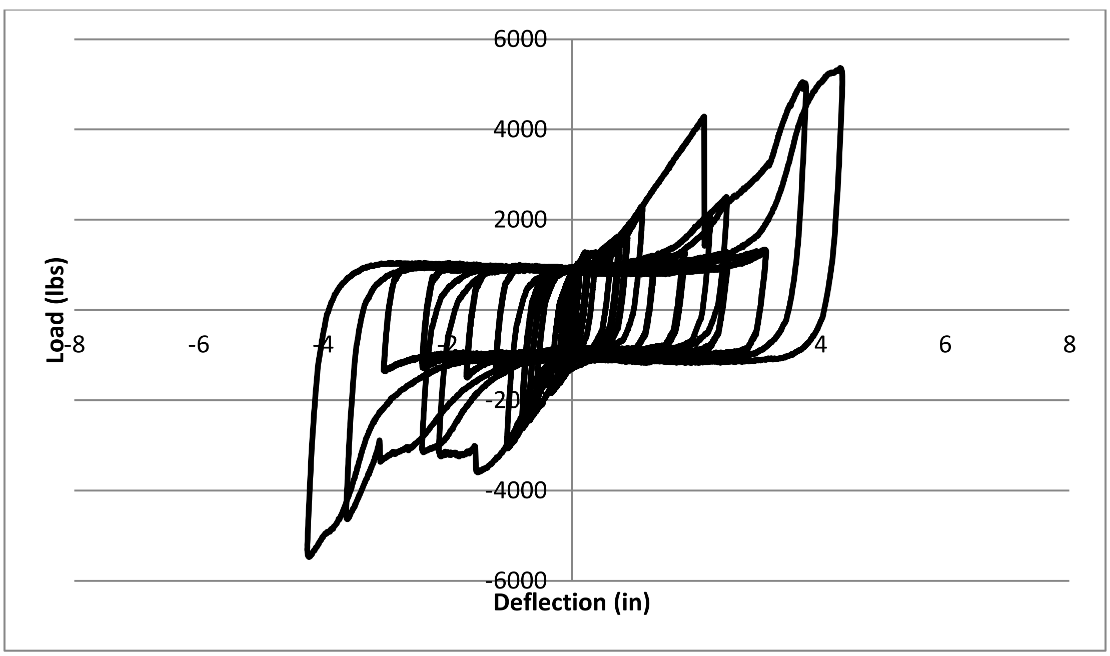

Figure 17: Control Test D-Cyclic Loading Response of OSB Shear Wall

Similar to the differences between OSB and bamboo shear walls in the monotonic loading scenario, bamboo shear walls showed increased ductility while decreased stiffness and strengths compared to the OSB shear walls as seen below.

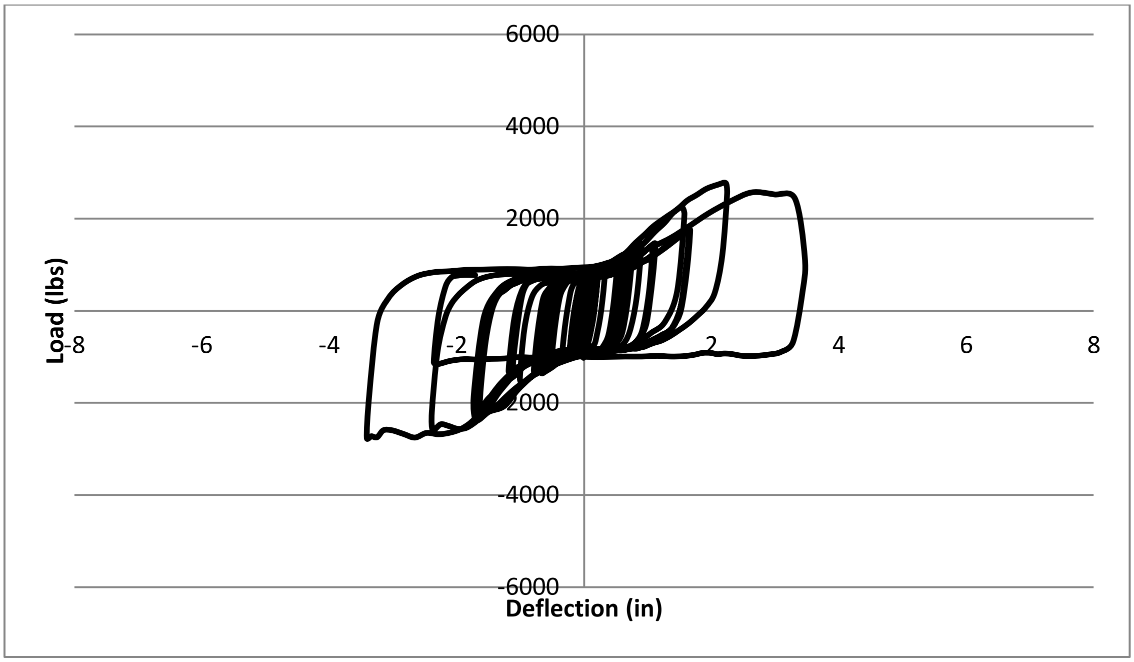

Figure 18: Proposed Test C-Cyclic Loading Response of Bamboo Shear Wall

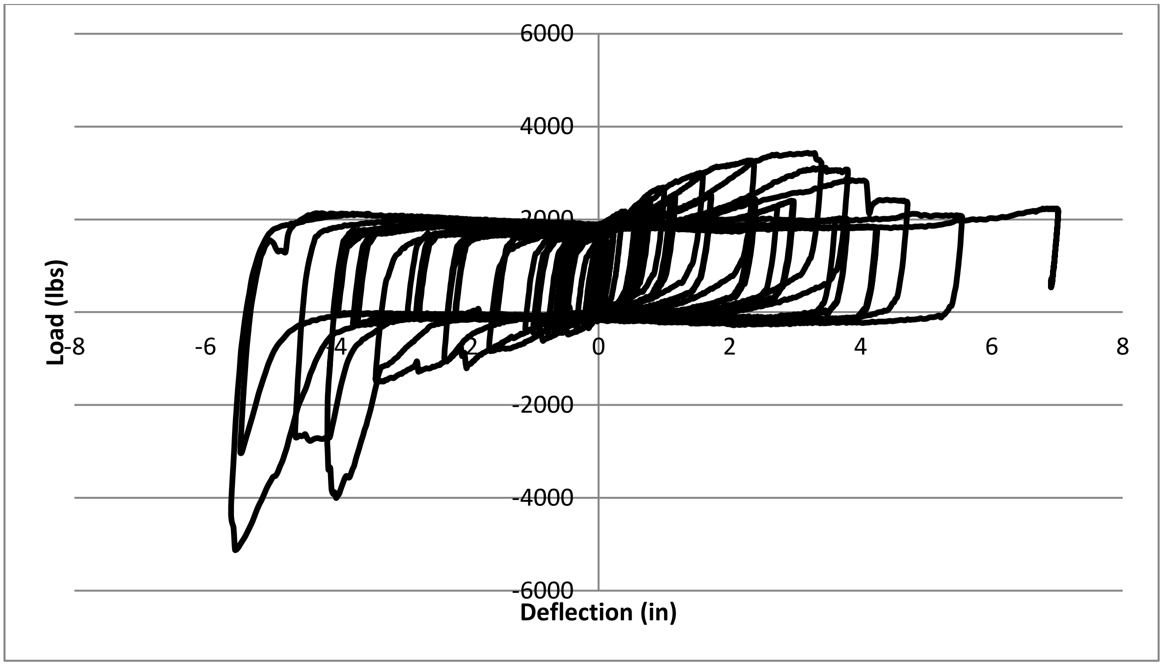

Figure 19: Proposed Test D-Cyclic Loading Response of Bamboo Shear Wall

After collecting and analyzing the important parameters as outlined in *Methods for Establishing Design Values on page X*, the process for determining strength and stiffness design values as well as the important seismic parameters for the proposed bamboo shear wall will now be shown.

9.0.0 Application of FEMA P-795 to Establish Design Values

By summarizing the parameters determined through the eight shear wall test results above, the following calculations can be made which will be used in the six equations as outlined below:

Table 9: Summary of Acceptance Criteria Evaluation for Proposed bamboo Shear Wall Component

Requirements Based on Cyclic-Load Test Data	
Ultimate Deformation Capacity (performance group)	$\sim\Delta_{U,PC} \geq \sim\Delta_{U,RC} P_U P_Q$
Ultimate Deformation Capacity (individual configurations)	$\sim\Delta_{Uj,PC} \geq (1\text{-}1.5\sigma_{\Delta u,RC})(\sim\Delta_{U,RC})\ P_U P_Q$
Initial Stiffness Ratio	$0.75 \leq \sim R_{K,PC} / \sim R_{K,RC} \leq 1.33$
Effective Ductility Capacity	$\sim\mu_{eff,PC} \geq 0.5\sim\mu_{eff,RC}$
Requirements Based on Monotonic-Load Test Data	
Ultimate Deformation Capacity (Option 1)	$\sim\Delta_{UM,PC} \geq \sim\Delta_{UM,RC} P_U P_Q$
Ultimate Deformation Capacity (Option 2)	$\sim\Delta_{UM,PC} \geq 1.2(\sim D_C)(\sim\Delta_{U,RC}) P_U P_Q$

Table 10: Summary of Component OSB Shear Wall Cyclic Test Results

	Strength			Stiffness			Ductility		Deformation Capacity
	V_M (lb)	V_D (lb)	$R_O = V_M / V_D$	K_L (lb/in)	K_D (lb/in)	$R_K = K_L / K_D$	$\Delta_{y,eff}$ (in/in)	μ_{eff}	Δ_u (in/in)
A	3348	1900	1.76	10820	5950	1.82	0.01	2.01	0.02
B	3585	1900	1.89	6410	5950	1.08	0.01	2.29	0.03
Average (Denoted by ~)	3470	1900	1.83	8620	5950	1.45	0.01	2.15	0.025
Standard Deviation	120	0	0.06	2200	0	0.37	0	0.14	0.01

Table 111: Summary of Component OSB Shear Wall Monotonic Test Results

	Strength			Stiffness			Ductility		Deformation Capacity
	V_M (lb)	V_D (lb)	$R_O = V_M / V_D$	K_L (lb/in)	K_D (lb/in)	$R_K = K_L / K_D$	$\Delta_{y,eff}$ (in/in)	μ_{eff}	Δ_u (in/in)
C	3630	1900	1.91	8280	5950	1.39	0.01	1.55	0.02
D	2330	1900	1.22	5140	5950	0.86	0.005	3.61	0.02
Average (Denoted by ~)	2980	1900	1.57	6710	5950	1.13	0.0075	2.58	0.02
Standard Deviation	650	0	0.34	1574	0	0.26	0.0035	1.03	0

Table 12: Summary of Proposed Bamboo Shear Wall Cyclic Test Results

	Strength			**Stiffness**			**Ductility**		**Deformation Capacity**
	V_M (lb)	V_D (lb)	$R_O = V_M / V_D$	K_L (lb/in)	K_D (lb/in)	$R_K = K_L / K_D$	$\Delta_{y,eff}$ (in/in)	μ_{eff}	Δ_u (in/in)
A	2770	TBD	TBD	6200	TBD	TBD	0.01	1.99	0.03
B	3430	TBD	TBD	6172	TBD	TBD	0.01	2.90	0.04
Average (Denoted by ~)	3100	TBD	TBD	6186	TBD	TBD	0.01	2.45	0.04
Standard Deviation	330	TBD	TBD	14	TBD	TBD	0	0.46	0.005

Table 13: Summary of Proposed Bamboo Shear Wall Monotonic Test Results

	Strength			**Stiffness**			**Ductility**		**Deformation Capacity**
	V_M (lb)	V_D (lb)	$R_O = V_M / V_D$	K_L (lb/in)	K_D (lb/in)	$R_K = K_L / K_D$	$\Delta_{y,eff}$ (in/in)	μ_{eff}	Δ_u (in/in)
A	2650	TBD	TBD	4800	TBD	TBD	0.02	2.16	0.05
B	1530	TBD	TBD	4140	TBD	TBD	0.003	8.52	0.02
Average (Denoted by ~)	2090	TBD	TBD	4470	TBD	TBD	0.01	5.34	0.04
Standard Deviation	560	TBD	TBD	330	TBD	TBD	0.01	3.18	0.014

Because FEMA P-795 requires pre-determined design values for applying the six equations in table 7, what will need to be done is to first run a statistical analysis of the proposed bamboo shear wall test results. By using an applied K-Factor to experimental peak strength and stiffness based on a 95% confidence limit and a 25% confidence interval of 4.162, the following design values were determined. A 95% confidence limit was used because of the recent acceptance criteria established by AC162 §3.3.1 and §3.3.2 and a 25% confidence interval was used because

Proposed Design Strength:

$$V_D = \tilde{V}m - K * \sigma \tag{1}$$

$$V_D = 2593\ lb - 2.617 * 532.25\ lb = 1200\ lb$$

$$\frac{V_D}{4} = \frac{1200lb}{4} = 300\ lb/ft$$

Proposed Design Stiffness

$$K_D = \widetilde{K}l - K * \sigma \tag{2}$$

$$K_D = 5329\frac{lb}{in} - 2.617 * 857\frac{lb}{in} = 3090\frac{lb}{in}$$

Before applying the acceptance criteria from *FEMA P-795,* the penalty factors for uncertainty and design strength difference must be applied. This information can be determined from tables 4 & 5.

Using the highest penalty factor for uncertainty because of the inconsistency of bamboo and to be conservative, a value of 1.40 was chosen. By determining the standard deviation for differences in peak strength, a value for P_Q of 1 was used. Now using the design values, the six equations from *FEMA P-795* can now be applied.

Acceptance Criteria Evaluation Factor 1: SATISFIED

$$\sim\Delta_{U,PC} \geq \sim\Delta_{U,RC}P_UP_Q \tag{3}$$

$$0.036\ \geq 0.026 * 1.4 * 1$$

$$0.036\ \geq 0.36$$

Acceptance Criteria Evaluation Factor 2: SATISFIED

$\sim\Delta_{U,PC} \geq (1\text{-}1.5\sigma_{\Delta u,RC})(\sim\Delta_{U,RC})\, P_U P_Q$ (4)

$0.036 \geq (1 - 1.5 * 0.007) * (0.026) * 1.4 * 1$

$0.036 \geq 0.0038$

Acceptance Criteria Evaluation Factor 3: SATISFIED

$0.75 \leq \sim R_{K,PC} / \sim R_{K,RC} \leq 1.33$

(5)

$$0.75 \leq \frac{1.73}{1.82} \leq 1.33$$

$0.75 \leq 0.95 \leq 1.33$

Acceptance Criteria Evaluation Factor 4: SATISFIED

$\sim\mu_{eff,PC} \geq 0.5\sim\mu_{eff,RC}$ (6)

$2.62 \geq 0.5 * 2.15$

$2.62 \geq 1.08$

Acceptance Criteria Evaluation Factor 5: SATISFIED

$\sim\Delta_{U,PC} \geq \sim\Delta_{U,RC} P_U P_Q$ (7)

$0.038 \geq 0.019 * 1.4 * 1$

$0.036 \geq 0.27$

Acceptance Criteria Evaluation Factor 6: N/A, only A.C. equation 5 or A.C. equation 6 must be satisfied.

All equations have thus been satisfied; therefore the seismic performance factors for OSB timber shear walls as outlined in ASCE 7-10 can be directly applied. The results for this process can be summed up in the following table and through this evaluation, credible design values for the proposed bamboo shear wall have been established.

Table 14: Summary of Final Results

Design Factor	OSB Stapled Shear Wall (Control)	Bamboo Shear Wall (Proposed)
V_D, Design Strength (LB/FT)	475	300
K_D, Design Stiffness (LB/IN)	5950	3090
R, Response Modification Factor	6.5	6.5
Ω, Overstrength Factor	3	3

10.0.0 Cost Analysis

We believe significant cost reductions can be achieved over conventional construction techniques using our bamboo shear walls. The ability to prefabricate a wall and simply tilt it into place allows for large savings in time and labor costs in the field. In addition, the controlled environment in which the prefabrication is completed will allow for quality control issues to be much more strictly monitored and reduce the possibility of errors being made in the field. These factors will ultimately drive down costs and increase the efficiency as well as the feasibility of bamboo shear wall systems.

11.0.0 Environmental Impact

The production of wood is a lengthy process and is not possible in many parts of the world due to the very particular requirements necessary for softwood trees to thrive. In developing nations without forestry controls, forests will be cleared of trees to provide timber, such as is happening in Brazil today. This widespread deforestation will lead to the extinction of untold numbers of species and allow topsoil erosion and its consequent desertification to ccur. A way to address the increased demand for construction materials while avoiding the associated environmental impacts is necessary if the Earth is to provide for future civilizations.

The unrestricted use of the most common residential building material, timber, will have devastating effects which cannot be understated. Our senior design team will therefore attempt to address the environmental shortcomings of timber by putting forth bamboo as an alternative building material for lateral force resisting systems in conventional light frame building construction. Many of the environmental problems associated with other building materials can be avoided through the use of bamboo. Unlike many species of timber, bamboo can be grown in almost any tropical or subtropical environments, which are conveniently where many developing countries are located. This will allow for building material in these nations to be locally sourced, cutting down on the need for In addition, bamboo grows at a speed much higher than that of timber, maturing within several years compared to the decades that it takes for most timber trees. This allows for the yields per grove to be much higher, reducing demand on land requirements. This rapid rate of growth also allows atmospheric carbon to be sequestered at a much higher rate than with softwoods, helping to reduce the greenhouse effects associated with high carbon dioxide levels. In addition, the production of bamboo requires much less energy than steel or concrete does, reducing demand on energy infrastructure and fossil fuels.

The use of bamboo as a lateral force resisting system for construction would allow the increasing demand on materials to be met while minimizing the detrimental effects on the environment. It would eliminate the need for large steel moment frames and concrete and wood shear walls while still allowing large numbers of people to provide housing and services without causing large amounts of destruction to the planet.

12.0.0 Conclusion

Our goal for this project was to develop a bamboo shear wall system and determine its equivalency as a structural component compared to conventional OSB shear walls in order to provide a sustainable alternative to current building practices. By taking into account different technical and non-technical factors, we guided the development of these walls into a system that is directly analogous to the current timber standard.

By using FEMA P-795 as a guideline, we designed, built, tested, and analyzed our data to determine ultimately that design strengths and stiffnesses were indeed comparable to conventional OSB walls. These results were verified and supported by the acceptance by a building official in the context of the 2013 Santa Clara Solar Decathlon Team.

The results of our testing and analysis give us confidence in our bamboo shear walls', and bamboo in general's, potential as a structural alternative to conventional construction methods.

14.0.0 References

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